

4.—Cainozoic stratigraphy in the Perth area¹

by Patrick G. Quilty²

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Abstract

The Cainozoic sequence in the vicinity of Perth is described. The two major sedimentary cycles recognised are Late Palaeocene-Early Eocene and Early-Middle Miocene. The former includes the Kings Park Formation (including the Mullaloo Sandstone Member, defined herein). The later cycle includes the Stark Bay Formation, also defined herein, and possibly an overlying poorly-known carbonate unit. The Mullaloo Sandstone Member is interpreted as a marine-deposited sand from the early Swan River, and the rest of the Kings Park Formation as a more southerly estuarine to marine unit. The Stark Bay Formation is a carbonate-chert formation deposited on the inner continental shelf. Age and ecological results are based on planktonic and benthonic foraminifera. *Lepidocyclina* aff. *howchini* Chapman and Crespin is recorded from Gage Roads No. 2. It indicates that there were warm waters in the Early Miocene all around the Australian coast and also that the warm water planktonic foraminiferal zonation may be used in the Miocene of the Perth Basin.

A fairly widespread Pliocene-Quaternary marine incursion is represented in the area by thin, discontinuous sediments with characteristic molluscan faunas.

Introduction

History of study

Several published papers have been concerned with the Tertiary palaeontology of the Perth Basin, mainly involving the Kings Park Formation onshore in the vicinity of Perth. Several unpublished results are also worthy of recognition. Recently, there has been an upsurge in interest in the younger Cainozoic and several preliminary papers have appeared. Tertiary sediments are not known from outcrop in the area under review, all evidence presented here having been gleaned from bore material.

The earliest work in the area was reviewed by Coleman (1952) and that will not be repeated here. The major palaeontological results are contained in papers by Parr (1938), Coleman (1952), Cookson and Eisenack (1961), and McGowran (1964). Relevant unpublished works are those by Pudovskis (1962) and Cockbain and Ingram (1967). Wells (1943) made a brief comment on a coral fauna and Glaessner (1956) described a crustacean from one of the bores.

Parr's (1938) paper was the first major contribution to the understanding of age relationships in the area. He examined in detail the foraminiferal fauna from the Kings Park No. 2 Bore and assigned an Eocene age by comparison with contemporary American studies, mainly by Cushman. This Eocene age was accepted for quite some time, although some aspects of the fauna were confusing.

Coleman (1952) examined more material from a total of six bores in the Perth metropolitan area. His paper carried two important footnotes. One foreshadowed the application of the name Kings Park Shale for the sequence studied. The other hinted at a possible Palaeocene age by comparison with contemporary studies in Sweden. Coleman recorded a more diverse foraminiferal fauna and several more groups of fossils than did Parr. He noted difficulties in biostratigraphic correlation in the Perth metropolitan area bores.

Cookson and Eisenack (1961) expanded the area of interest to the Rottnest Island Bore. Two samples from the Kings Park Formation interval were described as younger than Victorian time equivalents of the Kings Park Formation in its type section.

Pudovskis (1962), while still accepting the Late Eocene age for the Kings Park Formation, produced what is still the most detailed lithological correlation of wells in the area. His report used information from 38 wells spread from Pt. Peron and Rottnest Island in the west to the Midland Railway workshops and Helena Vale in the east.

McGowran (1964) restudied Parr's samples and concluded that the age of the Kings Park Formation in its type section (Kings Park No. 2) is Late Palaeocene, *Globorotalia pseudomenardii* Subzone of the *G. velascoensis* Zone of Berggren (1965) (*G. pseudomenardii* Zone of Bolli, 1957). This is the same as zone P4 in the comprehensive scheme of Blow (1969) as detailed by several authors including Berggren (1971). McGowran suggested that it was unlikely that the material in the Rottnest Island Bore (284-666 m) would be younger than that in Kings Park No. 2.

Cockbain and Ingram (1967) examined foraminifera and palynomorphs from the Rottnest Island Bore and recorded a Late Palaeocene to Early Eocene age for the sediments there.

No foraminiferal investigations have been made on bore material from the post-Miocene in the Perth area. However, Mr. G. W. Kendrick, W. A. Museum, has commenced detailed studies of molluscs (mainly bivalves) from shallow bores and from outcrops of the Coastal Limestone (Darragh and Kendrick, 1971; Kendrick, 1960). Enough information is available from his work to suggest that there are at least two post-Miocene episodes of marine sedimentation in the Perth area.

Scope of this investigation

All wells drilled offshore in the Perth Basin have been drilled for West Australian Petroleum Pty. Limited (WAPET). Study of the bores drilled to-date permits this summary to be made.

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² West Australian Petroleum Pty. Limited, Box C1580, G.P.O., Perth, Western Australia 6001.

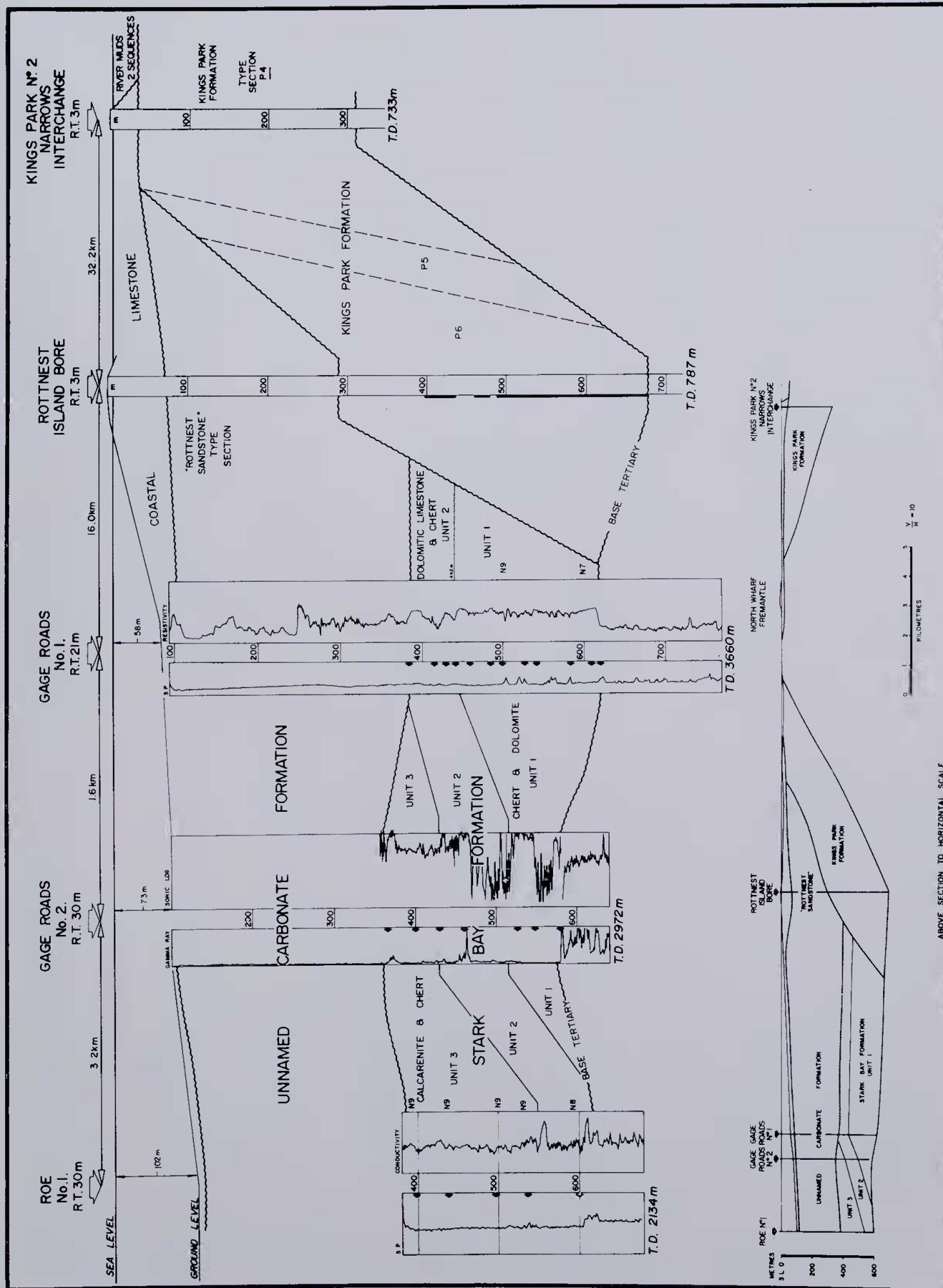


Figure 1.—Tertiary section Kings Park No. 2-Rce No. 1.

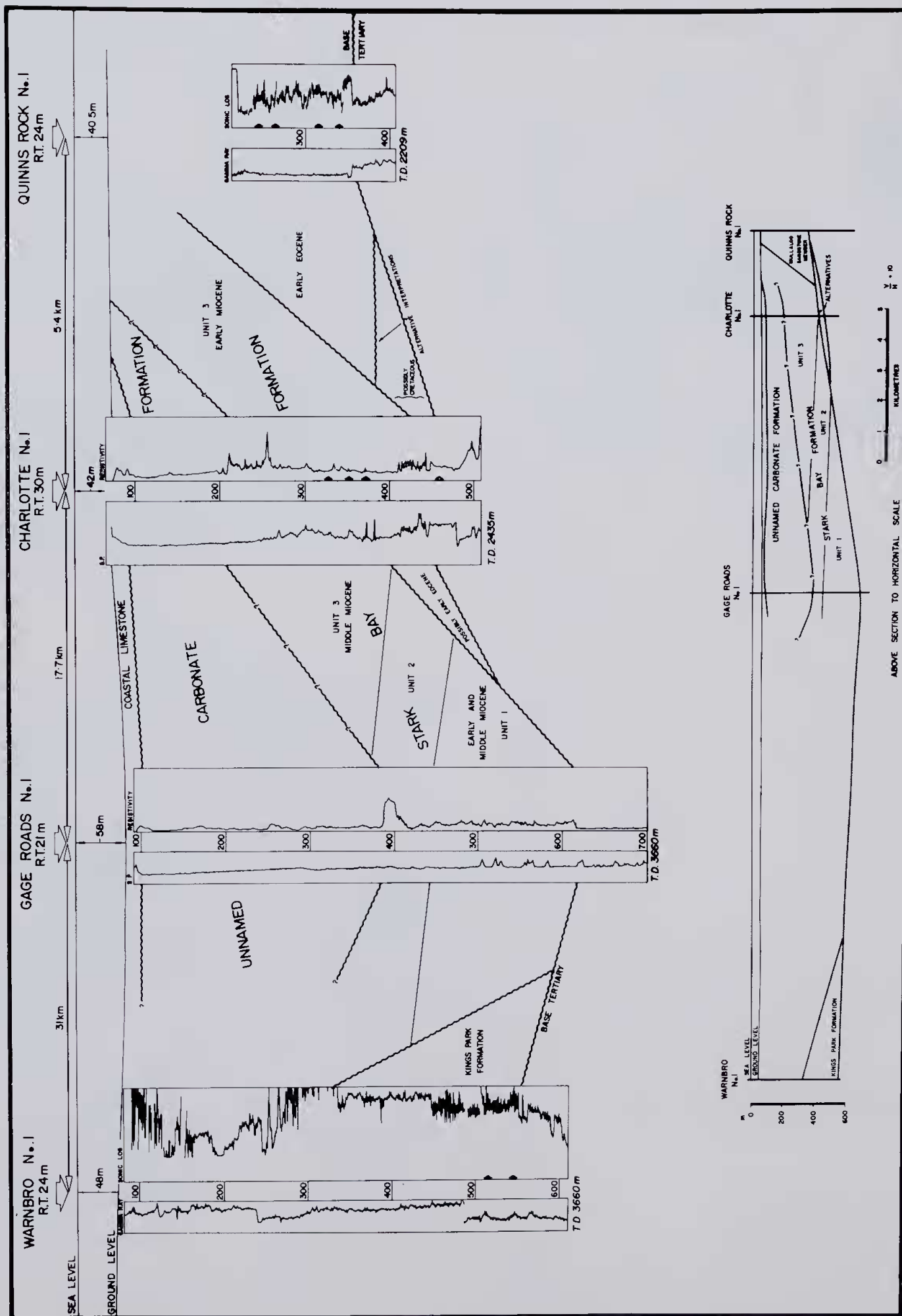


Figure 2.—Tertiary section Quinns Rocks No. 1-Warnbro No. 1.

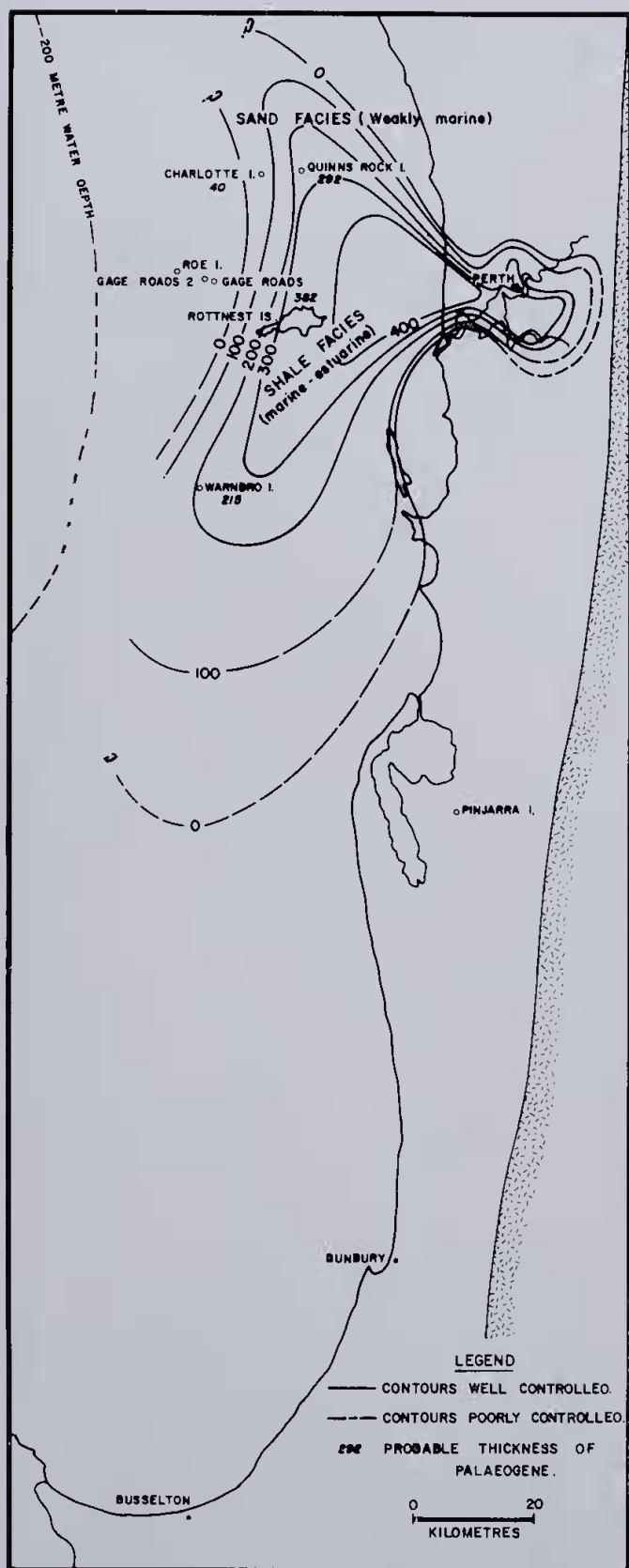


Figure 3.—Isopach and palaeogeographic map of the Kings Park Formation.

There is a large area of Tertiary, between the sequence in the Carnarvon Basin 1000 km to the north and in the Plantagenet Group, 400 km to the south from which little has been studied. Apart from the Kings Park Formation,

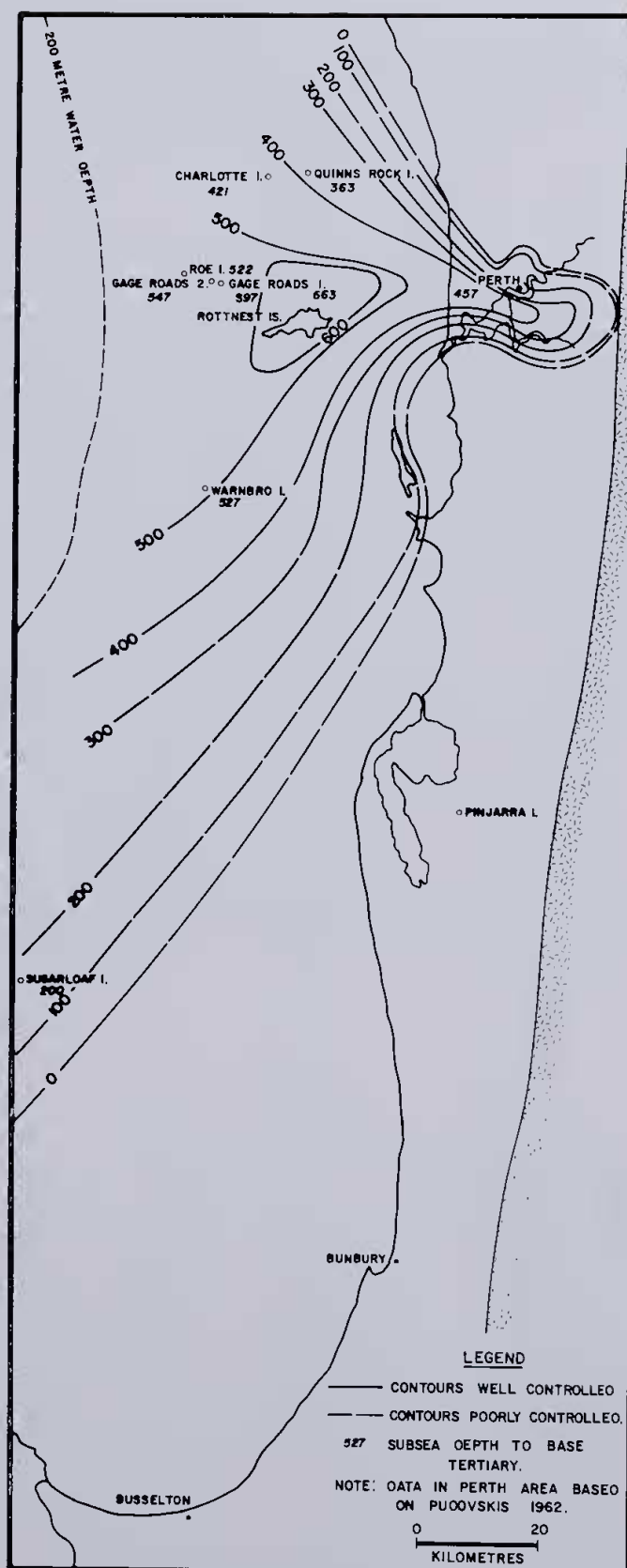


Figure 4.—Tertiary isopach and depth to base Tertiary.

no proven Tertiary marine faunas or lithological units have been defined yet from the Perth area.

This report deals mainly with the Palaeocene, Eocene and Miocene, but the younger sediments are noted briefly for completeness. Character-

istic foraminifera are illustrated on two plates. Figures 1 and 2 are compilations of the information detailed in the major part of this paper. Figures 3 to 5 show the palaeogeography and distribution of the units mentioned. Figures 6 and 7 give electric log and lithology of the new units defined and Figure 8 is a summary of the Cainozoic stratigraphy of the Perth area.

Sample reliability

The most reliable samples are from conventional cores (C) or sidewall cores (SWC). These are taken from the depth indicated. All available samples were used in this study.

In many cases, the only samples available are from ditch cuttings (DC). These samples are circulated to the surface in drilling mud and removed from the mud on vibrating screens. While they are usually fairly representative of the fauna at the depth taken, they may contain much downhole contamination, or rarely, may be entirely composed of contaminants. Ditch cuttings samples are of a much lower order of reliability than core samples.

Depth Measurements.—Throughout this work, depths mentioned are drill depths; this is, depths below the Rotary Table (R.T.). All measurements were originally recorded in feet, and have been converted to the nearest metre.

Repositories.—Rock specimens are held at the Geological Survey of Western Australia and at the Bureau of Mineral Resources, Geology and Geophysics, Canberra. The foraminifera figured on the plates are housed in the Palaeontological collection of the Geology Department, University of Western Australia and the number following the initials U.W.A.G.D. is the catalogue number in that collection.

Discussion of the sections examined

Kings Park area

No new material has been examined from the type section of the Kings Park Formation, as the age, fauna and lithology have been described adequately by Parr (1938), Coleman (1952) and McGowran (1964).

The Kings Park Shale was described in McWhae *et al.* (1958, p. 130) as consisting of "grey calcareous shales and claystones . . .". Pudovskis (1962) stated that it "consists predominantly of grey calcareous, glauconitic siltstones, shales and some sandstones. Some thin hard limestone beds are present in the lower part of the formation". The latter seems the better definition.

Samples have been examined cursorily from excavations at the Narrows Interchange Project and also from the old Celtic Club Bore on the corner of St. George's Terrace and Irwin St., Perth. Although faunas vary a little from those in the type section, the lithology appears identical and the age of P4 for the Kings Park Formation onshore is substantiated.

Overlying the Kings Park Formation at the Narrows Interchange site (Fig. 1) is a sequence of Quaternary deposits. At the base stratigraphically is the Coastal Limestone, which has

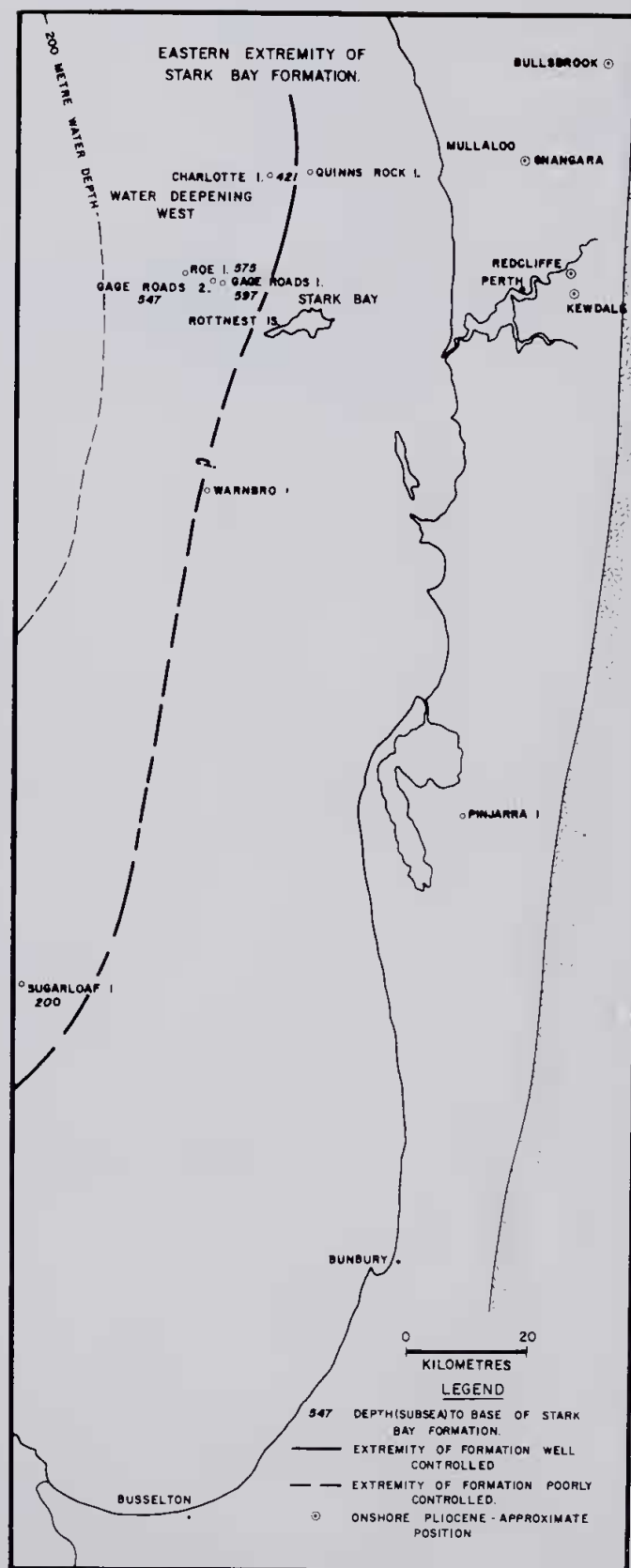


Figure 5.—Distribution of the Stark Bay Formation and of the Pliocene onshore.

been dated on Rottnest Island at about $100\,000 \pm 20\,000$ years BP (Teichert, 1967).

This formation (aeolian in the immediate vicinity) has been eroded by the Swan River and two sequences of estuarine muds succeed it. The older sequence is the more indurated and

is referred to as the "Blue Mud" by site engineers. It is distinctly older than the present sequence and contains abundant bivalves attesting to a marine or estuarine environment. No foraminifera were recovered from this material.

The younger sequence (deposited by the modern erosional cycle) is referred to as the "Black Mud".

The Quaternary sequence extends to approximately 37 m below sea level. The relationships are illustrated diagrammatically in Figure 1.

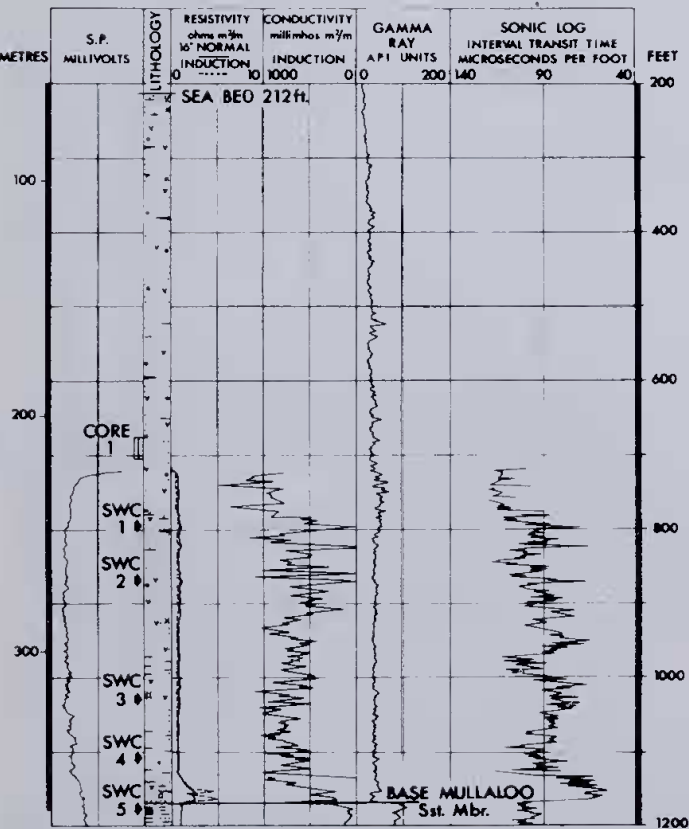


Figure 6.—Lithological and log characters of the Mullaloo Sandstone Member of the Kings Park Formation.

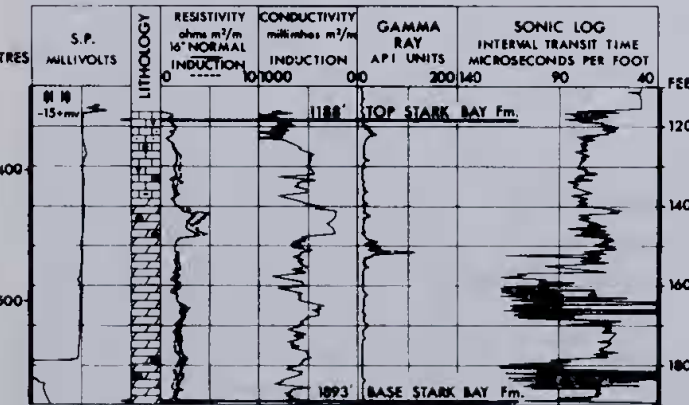
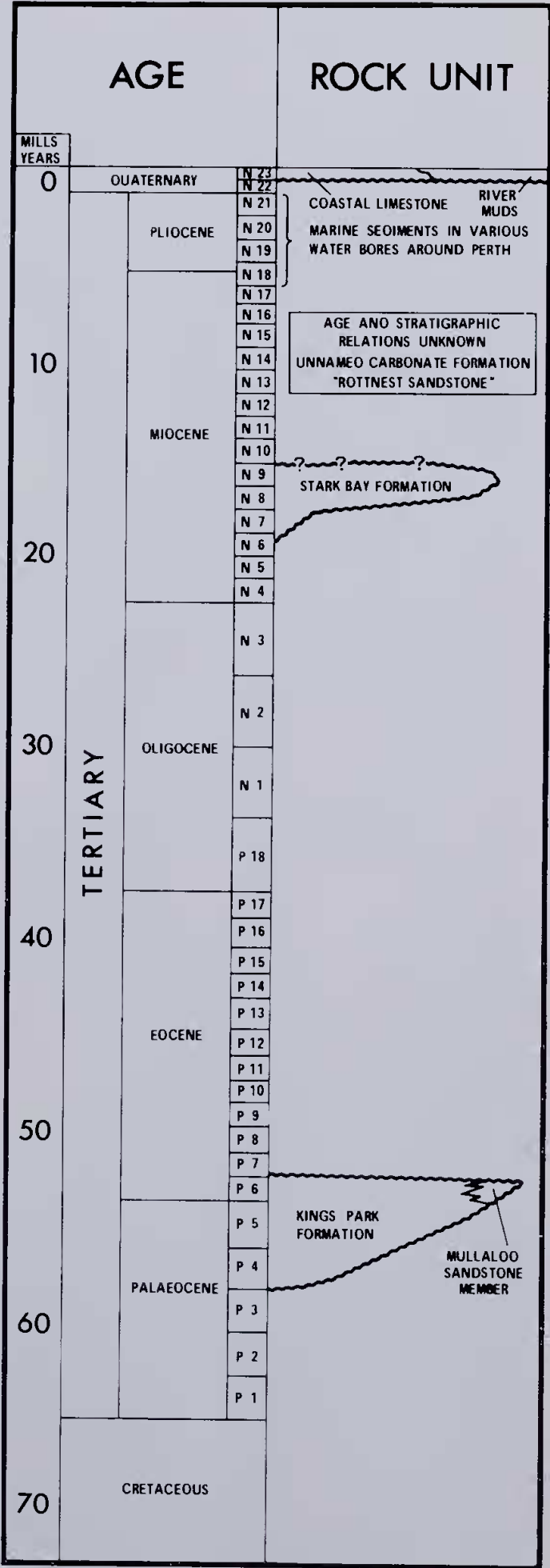


Figure 7.—Lithological and log characters of the Stark Bay Formation.

Figure 8.—Stratigraphic column for the Cainozoic of the Perth Area.



The Rottnest Island Bore (Fig. 1) was drilled in 1913 in an unsuccessful quest for artesian water. No samples were preserved between the surface and 390 m. Below 390 m cores were preserved representing the intervals marked on Figure 1.

284-666 m: *Kings Park Formation*. All cores recovered are from a lithology identical with the Kings Park Formation in its type section, although there is a slight but significant age difference between the formation on Rottnest Island and in its type section. Although there is the possibility of a stratigraphic break between the two sections, it seems probable that they are continuous and the name Kings Park Formation is taken as valid for the section in the Rottnest Island Bore.

The top of the formation (284 m) is based on drillers' records. The upper part (284-451 m) consists of grey argillaceous sandstone, and the lower part (451-666 m) of grey shale.

Only one sample from this well is present in the WAPET collections—that from the interval 486-616 m. Through the courtesy of Messrs J. H. Lord, B.S. Ingram and Dr A. E. Cockbain, of the Geological Survey of Western Australia, I have been able to examine material from the following four intervals in the Rottnest Island Bore: 451-470 m; 480-486 m; 486-616 m; and 617-666 m.

The shallowest sample contains an unidentified *Pseudohastigerina* (*wilcoxensis* or *pseudoiota*), *Globorotalia aequa* Cushman and Renz, and *Globigerina* of the *linaperta* group. This fauna indicates a *Globorotalia rex* Zone (P6) age.

The fauna from 480-486 m and 486-616 m is virtually identical. That from 617-666 m is a little different but there is no recognisable age difference. The main forms present are *Pseudogloboquadrina primitiva* Finlay, *Globigerina* of the *linaperta* group, *Globorotalia aequa* and *G. broedermanni* Cushman and Bermudez. This also supports a P6 age.

The benthonic content of all faunas is typical of the Kings Park Formation and many other sections in Australia of Palaeocene age.

71-284 m: "*Rottnest Sandstone*". McWhae (*pers. comm.*) informally used this name for "... 700 feet thickness of friable, fine to coarse, and conglomeratic sandstones, red and brown in colour and unfossiliferous, probably continental in origin".

This formation is not known outside the type locality. It also seems that no representative collections of it are available now. Thus, the name remains informal and the quotation marks used are appropriate. It could be part of the Kings Park Formation, an equivalent of the Stark Bay Formation or even younger.

0-71 m: *Coastal Limestone*. This record also is based on drillers' records and no samples are known from the well. Teichert (1967) recorded an age of $100,000 \pm 20,000$ years BP for marine fossils from this formation on Rottnest Island.

Gage Roads No. 1 was the second offshore oil well drilled in the Perth Basin.

For this study, the following samples have been examined:

Depth	Sample Type
107-116 m	DC*
116-125 m	DC
301 m	C**
302 m	C
303 m	C
329-338 m	DC
393-402 m	DC
415 m	SWC†
430 m	SWC
442 m	SWC
463 m	SWC
466-475 m	DC
472 m	SWC
486 m	SWC
502 m	SWC
512-521 m	DC
527 m	SWC
542 m	SWC
583 m	SWC
594-604 m	DC
604-610 m	DC
620 m	SWC

* Ditch Cuttings

** Conventional Core

† Sidewall Core

From these samples, from log interpretation and from wellsite sample examination, the following intervals are recognised in the well. Faunas in general are poor. The best samples for dating purposes are from 502 m and 604-610 m.

80-?100 m: *Coastal Limestone*—Pleistocene: The well spudded in Coastal Limestone whose thickness is unknown but is probably thin, certainly less than 30 m as the ditch cuttings at 94 m are of the underlying formation.

?100-389 m: *Unnamed Limestone Formation*—Pliocene-Miocene: The formation consists of yellow and pink calcarenites, clearly of biological origin in the upper region. Recrystallisation has destroyed most fossils but the shallow ditch cuttings contain abundant large foraminifera *Amphistegina lessonii* d'Orbigny and a species of *Operculina* which Barker (1960) refers to *O. ammonoides* (Gronovius). The species found here is the same as that figured by Barker but whether or not it is *O. ammonoides* is open to doubt, as was pointed out by Barker. This species makes up 60-70% of the foraminiferal fauna.

The age of the fauna cannot be defined more accurately than post-Oligocene. The sediment accumulated in warm, shallow marine conditions. The relationship of this formation with the overlying Coastal Limestone is probably unconformable. The nature of the contact with the sediment below is unknown.

389-619 m: *Stark Bay Formation* (new formation, defined later)—Early to Middle Miocene: The upper limit is taken at the marked log changes (resistivity) at 389 m and the lower limit at another marked change from the South Perth Formation (Cretaceous). Thirteen samples have been examined from this section.

The entire section is basically dolomite or dolomitic limestone, and can be divided into

two subintervals on the basis of lithological variation.

(a) 389-442 m (approximately). Dolomite unit.

This interval consists of dolomites, grey in colour, barren of foraminifera and devoid of any primary features.

(b) 442-619 m Cherty unit.

This unit also contains much dolomite but grey and brown chert is dominant in the samples seen and lithological characters are more variable than in the above section.

The chert contains abundant sponge remains and silicified calcareous fossils such as foraminifera.

The age control for the whole formation is based on the sidewall core at 502 m which contains a poorly preserved but dateable fauna. Forms present include *Globigerinoides sicanus* de Stefani, *G. quadrilobatus trilobus* Reuss, *Globigerina* cf *G. euapertura* Jenkins and *Globorotalia obesa* Bolli. These place the fauna in the Burdigalian (upper half of the Early Miocene) or lowest Langhian (N8-N9). The fauna is 25% planktonic species suggesting deposition in 30-60 m of water. This is supported by the presence of more than 10% of bolivinid species. An interesting benthonic form in this fauna is *Pavonina triformis* Parr.

Another sample yielding a good fauna is that from the interval 604-610 m. This contains *Globorotalia barisanensis* LeRoy, *Globigerina woodi woodi* Jenkins and *Sherbornina cuneimarginata* Wade. The age is slightly older than other Miocene records, probably about N7 (lower half of *Globigerinatella insueta* Zone of Bolli, 1957).

The lower boundary of this section is marked by the log change at 619 m which represents a transition from dolomite and chert above overlying a barren, fine sandstone of Cretaceous age below.

Gage Roads No. 2

Samples examined from this well are as follows:

Depth	Sample Type
C. 305 m	Cuttings from blade of 20" bit
366 m	SWC
369-372 m	DC
396-399 m	DC
402 m	SWC
424-427 m	DC
430 m	SWC
451-454 m	DC
461 m	SWC
488-490 m	DC
515-518 m	DC
527 m	SWC
543-546 m	DC
549 m	SWC
579 m	SWC
579-582 m	DC

Lithology.—From examination of logs, ditch cuttings and sidewall cores, the following lithological divisions are recognised in the well.

1. Ground Level—? "Coastal Limestone".

The well spudded in carbonate sediment, probably still forming under marine conditions and identical with marine members of the Coastal Limestone. Its thickness is unknown, but is probably not great. Its base is not indicated on the logs. A

thickness of the order of 30 m or less is envisaged as this is a "normal" thickness for the formation.

2. ?—approximately 362 m. Unnamed carbonate formation.

Only a single sample is available from this interval. It is a bulk sample taken from the blades of the bit at about 304 m. While a poor sample, it gives some indication of the lithology at this depth. It consists of recrystallised red to yellow limestone, slightly indurated with almost all organic structure obliterated. Some forms are recognisable as foraminifera. None are identifiable. It is the same lithology as that occurring at about the same depth in Gage Roads No. 1 and Roe No. 1.

The lower boundary is taken at 362 m as there is a marked sonic log change there, and the sample at 366 m is different.

3. 362-577 m Stark Bay Formation.

3a. 362-427 m.

Several samples in this interval show that at least in part the sediment consists of white bryozoan calcarenites with rich, well preserved foraminiferal faunas. There is also grey to pale brown dolomite in most samples.

This member seems absent from Gage Roads No. 1, but a much thicker sequence is found in Roe No. 1. It may represent the original lithology of the formation, diagenesis being responsible for the lithology below.

3b. 427-514 m.

Sample control in this interval is poor, the only sidewall cores being at 430 m and 461 m. The lithology of these cores is identical and consists of saccharoidal, friable brown crystalline dolomite with minor pyrite. No fossils are identifiable. The upper and lower boundaries are selected from sonic logs.

3c. 514-544 m.

This interval is known from a sidewall core at 526 m which consists of brown, friable, saccharoidal dolomite, markedly coarser than in the interval above.

3d. 544-577 m.

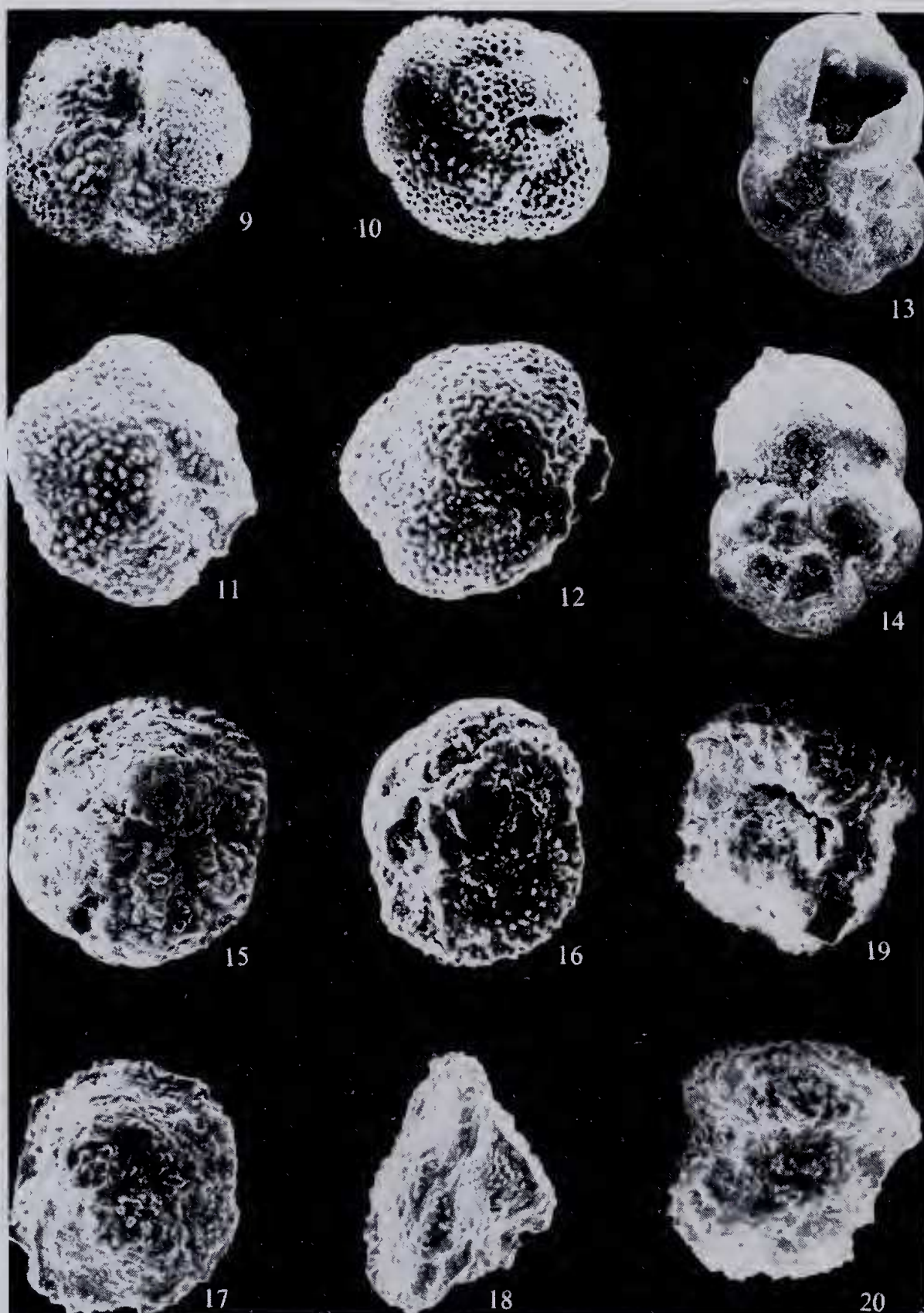
Lithology here is recorded in a sidewall core at 549 m and in a very distinctive ditch cuttings sample at 579-582 m.

Lithology in the interval is variable. The sidewall core at 549 m is a mixture of powdery white unaltered calcarenite with brown dolomite and chert. Thus, diagenetic change in this interval is not so complete as above. The sample has minor iron oxide staining.

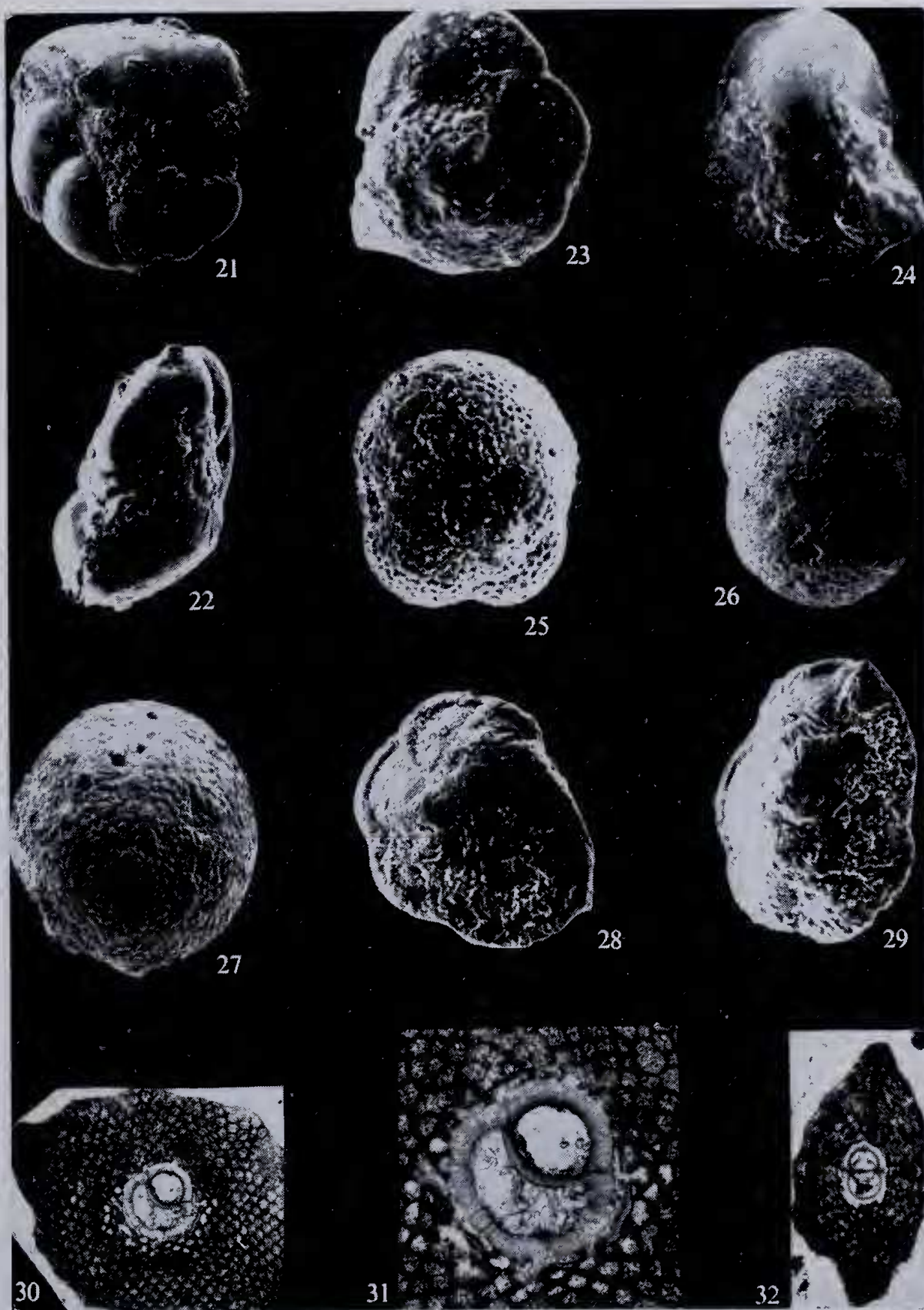
The ditch cuttings sample from 579-582 m consists almost entirely of downhole contamination, probably from just above the Cretaceous-Tertiary contact, here taken as 577 m—a sonic log pick. A sidewall core at 579 m is part of the underlying Cretaceous section. The ditch cuttings sample is partly of lightly iron-stained calcarenite with a well preserved foraminiferal fauna. The lithology and fauna are very characteristic, and have not been encountered above. They are thus probably very close to *in situ*.

The faunas.—No satisfactory faunas occur in samples above 366 m, the top sidewall core. Also, faunas in ditch cuttings between 427 m and 544 m must be suspect and probably represent downhole contamination. Thus faunas from sidewall cores at 366 m, 402 m and 549 m, as well as ditch cuttings between 366-427 m and 544-577 m, can be taken as representative of faunas at those depths. All faunas appear to belong to the N8-N9 interval of Blow (1969).

Samples from above 427 m and possible contaminated samples as deep as 518 m contain *Orbulina universa* d'Orbigny, *Globorotalia archeomenardii* Bolli, *Globoquadrina dehiscens* Chapman, Parr and Collins, and occasionally *Globigerinoides sicanus*. Thus these



Figures 9, 10.—*Globigerina mckannai* White, Warnbro No. 1, 552 m (ditch cuttings), X120. UWAGD 70421.
 Figures 11, 12.—*Globorotalia pusilla laevigata* Bolli, Warnbro No. 1, 552 m (ditch cuttings), X180. UWAGD 70422.
 Figures 13, 14.—*Globorotalia chapmani* Parr, Warnbro No. 1, 552 m (ditch cuttings), X100. UWAGD 70423.
 Figures 15, 16.—*Globorotalia dolabrata* Jenkins, Quinns Rock No. 1, 263 m (sidewall core), X130. UWAGD 70424.
 Figures 17, 18.—*Globorotalia velascoensis parva* Rey, Warnbro No. 1, 552 m (ditch cuttings), X130. UWAGD 70425.
 Figures 19, 20.—*Pseudoglobobulina primitiva* (Finlay), Warnbro No. 1, 552 m (ditch cuttings), X165. UWAGD 70426.



Figures 21, 22.—*Pseudohastigerina* sp. Rottnest Island bore, 486-616 m, X190. UWAGD 70427.
 Figures 23, 24.—*Globorotalia pseudomenardi* Bolli, Warnbro No. 1, 552 m (ditch cuttings), X250. UWAGD 70428.
 Figure 25.—*Globigerinoides sicanus* de Stefani, Gage Roads No. 2, 582 m (ditch cuttings), X140. UWAGD 70429.
 Figure 26.—*Praeorbulina transitoria* (Blow), Gage Roads No. 2, 582 m (ditch cuttings), Xc.150. Specimen lost since photography.
 Figure 27.—*Orbulina universa* d'Orbigny, Gage Roads No. 2, 454 m (ditch cuttings), X110. UWAGD 70430.
 Figures 28, 29.—*Globorotalia archeomenardi* Bolli, Gage Roads No. 2, 399 m (ditch cuttings), X150. UWAGD 70431.
 Figures 30-32.—*Lepidocyclina* cf. *howchini* Chapman and Crespin, Gage Roads No. 2 (ditch cuttings). 30, 31.—399 m (ditch cuttings). Equatorial section, UWAGD 70432. 30 x 40; 31 x 90. 32.—427 m (ditch cuttings). Vertical section, X40. UWAGD 70433.

samples all appear to belong to N9 (approximately the *Globorotalia fohsi barisanensis* Zone of Bolli, 1957).

The deepest sample (579-582 m) is different, with *Globigerinoides sicanus* and *Praeorbulina transitoria* Blow. An age of N8 is thus indicated.

A most interesting aspect of the faunas from the upper part of the section (especially 350-425 m) is the presence of *Lepidocyclina* in ditch cuttings. The significance is discussed later.

Roe No. 1

The samples studied are from sidewall cores at 399 m, 439 m, 498 m, 537 m and 600 m. No samples are available above these depths.

The well spudded in calcarenites identical with parts of the Coastal Limestone. As in the other wells in this vicinity, it seems that the Coastal Limestone may still be forming here under marine conditions, as samples brought to the surface by divers consist of weakly consolidated shell fragments and quartz grains. The shells still retain their original colour. The formation's thickness is unknown, again probably of the order of 30 m or less.

The top four sidewall cores all contain abundant, well preserved foraminiferal faunas in a clean, white bryozoan calcarenite. There may be very minor development of chert and dolomite. This unit is the same as that seen in Gage Roads No. 2 but not in Gage Roads No. 1.

The sidewall core at 600 m has a much more poorly preserved fauna in a dolomitic unit with chert. This unit also occurs in Gage Roads Nos. 1 and 2.

The boundary between the two units is not well marked lithologically but could be taken at 552 m on a marked sonic log change. The base of the Tertiary section is well marked at 616 m by sonic and electric log changes.

The faunas.—The upper calcarenite unit contains abundant planktonic foraminifera including *Orbulina universa* (to 537 m), *Globoquadrina altispira globosa* Bolli, and *Globigerinoides quadrilobatus immaturus* LeRoy. *Globorotalia* seems to be absent. By comparison with Gage Roads No. 1, this interval can be expected to be N9 in age.

The lowest sidewall core contains a different, poorly preserved, small fauna with *Globigerina euapertura*. Also by comparison with the lower reaches of Gage Roads No. 2, and by virtue of the apparent absence of *Orbulina*, this sample may be taken as N8 in age.

Quinns Rock No. 1

The following samples have been examined from this well:

Depth	Sample Type
243 m	SWC
263 m	SWC
314 m	SWC
337 m	SWC
358 m	SWC
335-344 m	DC

Lithology.—The lithology encountered in the Tertiary section of this well is different from that encountered in any other sections discussed in this report (Figs. 2, 6).

There is no "Coastal Limestone" section and the well spudded in quartz sandstone.

65-356 m: *Mullaloo Sandstone Member* of the Kings Park Formation (defined below)—Early Eocene. The entire Tertiary section consists of sandstone which Bozanic (1969) described as "... characterized by the abundance of discrete fine to granule (2-4 mm) sized, well to very well-rounded quartz grains. The colour of the quartz is mostly clear and milky white with minor amounts of pale yellow and pale brown. Many of the grains are frosted. Sidewall cores indicate that most of the free quartz grains as observed in drilling samples are lightly cemented by argillaceous material before being drilled".

"A number of mostly fine grained but locally ranging from fine to coarse grained sandstone interbeds are present. The quartz grains vary from subangular to subrounded. Fine to medium sized grains of black glauconite are present and fine mica flakes locally common. The sandstone is variably cemented by calcareous, kaolinitic, argillaceous and pyritic material."

"Carbonaceous and lignitic streaks and fragments—often pyritized—are not uncommon."

"Siltstone zones are also developed. They are light grey, with fine and very fine black glauconite grains and cemented by calcareous and argillaceous material."

The Faunas.—All samples examined but one, are sidewall cores and thus the samples can be regarded as *in situ*.

Only two samples contain any very significant foraminifera. They are at 263 m and 314 m.

The sample at 263 m contains two identifiable specimens. They are *Globocassidulina subglobosa* (Brady) and *Globorotalia dolabrata* Jenkins. Thus this sample is Early Eocene (*Globanomalina wilcoxensis* to *Globorotalia crater crater* zones of Jenkins, 1971). Equivalence between Jenkins's and Blow's (1969) scheme is not yet precise, but the age of the sample in Blow's scheme is P6-P7 approximately, about the same age as the Eocene sediments in the Rottnest Island Bore.

The fauna at 314 m is less well dated. Again it consists of few specimens. Present are *Pseudogloboquadrina primitiva* and *G. cf. taroubaensis* Bronnimann, which support the Early Eocene age indicated for the sample above at 263 m.

The other sidewall core samples are barren except for a single "*Cibicides*" *umbonifer* Parr at 337 m. The ditch cuttings sample from 344 m contains a small, well preserved Tertiary fauna including *Globigerina triangularis* White, which is consistent with the ages determined above.

The sidewall core sample at 360 m contains a Cretaceous fauna and the base of the Tertiary is taken at the electric log-lithology change at 356 m.

Charlotte No. 1

The section in Charlotte No. 1 (Fig. 2) has been examined from the following samples:

Depth	Sample Type
329 m	SWC
332 m	SWC
332-335 m	DC
354 m	SWC
363-366 m	DC
375 m	SWC
393-396 m	DC
396 m	SWC
424-427 m	DC
462 m	SWC

Lithology.—Lithology from sidewall cores and ditch cuttings is uniform between 328 m and 396 m. The electric log characters of this interval are consistent up to 209 m. and down to 411 m. Thus the interval 200-411 m can be taken as one lithological unit.

The sidewall core at 462 m is a clean, angular, feldspathic sand shown palynologically to be Lower Cretaceous, and the ditch cuttings at 427 m (in an interval of severe circulation problems) contain much clean rounded quartz sand. Thus the Cretaceous-Tertiary boundary could be taken at the log change at 411 m. However, it is possible that the interval 411-451 m, a distinct part of the logs, is Tertiary sandstone, equivalent to the Early Eocene sands in Quinns Rock No. 1. This is unproven as no early Tertiary fossils are known from this interval. Thus the Cretaceous-Tertiary boundary could be taken alternatively at 451 m.

The following lithological units can be recognized in the well.

1. 73 m (Seabed)—93 m (approximately). "Coastal Limestone".

Material brought to the surface from the seabed consists mainly of shell fragments and may be presently forming Coastal Limestone.

2. 93 m—209 m. Lithology unknown.

This interval may be equivalent to the "Rottnest Sandstone" but no samples were taken during drilling.

3. 209-411 m Stark Bay Formation. Early to Middle Miocene.

Samples are very uniform in lithology throughout this interval. They consist of moderately recrystallised friable white to grey calcarenites with no terrigenous content. Much of the recrystallisation is to pale translucent rhombs which react readily with cold HCl. Much of the original sediment appears to be echinoderm and bryozoan debris.

Chert is virtually absent from the section except perhaps in the lower portion. Chert fragments do occur in the ditch cuttings at 427 m.

The Faunas.—Samples from the Miocene section in this well all contain almost identical faunas. *Cibicides* (*sensu lato*) makes up 50-90% of all faunas, planktonic species (undiagnostic) occur in only one sample (354 m) where they constitute only 3% of the fauna, and buliminid species make up to 24%. Other elements are chiefly cassidulinids. Benthonic species are identical with those from the Miocene sections identified elsewhere in this work. Thus a combination of lithology and benthonic fauna indicates that this is part of the Miocene sequence in the area.

The following time division is therefore possible in the well:

73-93 m	(approximately)	Quaternary
"Coastal Limestone"		
93-209 m	Unknown (?)	"Rottnest Sandstone"
209-411 m	Early to Middle Miocene	
411-451 m	? Early Eocene Sandstone.	

Warnbro No. 1

The following samples have been examined:

Depth	Sample Type
512-515 m	DC
515 m	SWC
546 m	SWC
549-552 m	DC

Lithology.—All samples are typical Kings Park Formation (Fig. 2) of calcareous shales and siltstones with abundant quartz residue. Glauconite is very common.

The sonic log character is consistent to 337 m, where the formation top is placed. An alternative top, based on gamma ray logs, could be 241 m. The lower boundary at 552 m is based on sonic logs and on lithological and faunal change.

The faunas.—The best fauna is in the sidewall core at 515 m which, while diverse, contains few age diagnostic species. The age diagnostic species *Globorotalia pseudomenardii* Bolli and *G. chapmani* Parr occur in ditch cuttings at 552 m. Thus a P4 age is indicated.

Sugarloaf No. 1

Sugarloaf No. 1 is not listed on the accompanying diagrams as no *in situ* Tertiary material was examined from the well.

The uppermost sidewall core in the well is at 321 m and this, from palynology, is a Cretaceous argillaceous sandstone. The only evidence of Tertiary seen in material from this well is in ditch cuttings at 366 m. The sample is heavily contaminated with rocks from uphole, including pale brown chert, identical with that common in Unit 1 of the Stark Bay Formation (see below).

Thus, while no Tertiary fossils have been identified from the well, the Miocene sediments of the Perth area can be inferred to be present this far south.

Stratigraphic units

Rocks of at least three different cycles of deposition occur in the area and are best discussed in the context of these cycles.

The Palaeocene-Eocene cycle

One formation with one new member is recognised in this cycle.

The Kings Park Formation (Kings Park Shale of Fairbridge, in Coleman, 1952) occurs quite extensively onshore and was defined from the interval 37-302 m in Kings Park No. 2 Bore. Where present in cores in the metropolitan area, the thickness is usually of the order of 200-250 m but in South Perth Bore it reaches about 450 m and may be even a little thicker in the Claremont area (Fig. 3).

Offshore thicknesses are 216 m in Warnbro No. 1 and 382 m in the Rottnest Island Bore.

Lithology is variable, and for this reason, the name formation is preferred to shale. The dominant rock type appears to be calcareous shale and siltstone, usually glauconitic, but in places limestone and sandy facies are dominant. Examination of lithology logs presented by Pudovskis (1962) shows that sandstone is more abundant than indicated in other literature.

The fauna includes bryozoa, foraminifera, small molluscs, rare ostracods, common sponge spicules, etc.

The age varies from place to place. All on-shore samples seen are Late Palaeocene (P4) on the basis of planktonic foraminifera. This is also the age in Warnbro No. 1 offshore. In the Rottnest Island Bore it is Early Eocene (P6). No rocks of P5 age are yet known and it may be that what is included here in the one formation could belong to two deposition cycles with a minor unconformity or disconformity between. However, until this possibility is proven or disproven, all is included in one formation. P5 could very easily be represented by a thin section and be missed in this analysis.

Whether P4 or P6 in age, the lithology and fauna are almost identical indicating a similar environment of deposition. Planktonic foraminifera are not abundant and all other faunal elements are consistent with shallow (perhaps of the order of 30 m or less) water depths, probably in a large embayment or estuary.

The *Mullaloo Sandstone Member* (new name)

Type section: WAPET's Quinns Rock No. 1 in the interval 65-356 m.

Coordinates: Latitude 31° 48' 01" S; Longitude 115° 30' 52" E.

Derivation of name: The suburb and beach of Mullaloo, approximately the closest land to the well.

Thickness: In the type section: 292 m. Elsewhere: Charlotte No. 1 (411-451 m) 40 m.

Lithology: The member consists of poorly sorted, fine to very coarse quartz sandstone with angular to rounded grains. The rock has an argillaceous matrix and commonly is slightly glauconitic. Further details of the lithology are included in the discussion of Quinns Rock No. 1.

Extent: The member is so far identified positively only in Quinns Rock No. 1 although the identification in Charlotte No. 1 is also probably correct. The sandstone in that section is of rounded quartz grains, very similar to the type section. As the lithology has not been shown to be widespread, the unit has been defined as a member only. It is the same age as the younger part of the Kings Park Formation and is continuous with it. The consistent, distinctive lithology supports its recognition as a new member.

Fauna and age: The only fossils so far recovered are rare foraminifera, including *Globrotalia dolabrata* Jenkins which indicates an Early Eocene (P6-P7) age. It is thus a lateral time equivalent of part of the Kings Park Formation.

Relations of boundaries: The upper boundary is an unconformity with the Miocene carbonates (Stark Bay Formation).

The lower boundary is an unconformity with the Lower Cretaceous sediments below.

The Miocene Carbonate cycle

The full extent of this cycle of deposition is not known. One formation (Stark Bay Formation) is defined to include the white calcarenites, brown dolomites and cherts common north and west of Rottnest Island (see below).

The relationship of the overlying red and brown calcarenites is unknown, and a new formation name may eventually be necessary to describe that unit.

The *Stark Bay Formation* (new formation) (Fig. 7)

Type section: WAPET'S Gage Roads No. 2 in the interval 362-577 m.

Coordinates: Latitude 31° 57' 05" S, Longitude 115° 21' 45" E.

Derivation of name: Stark Bay, Rottnest Island, one of the closest named geographical features.

Thickness: In the type section 215 m. Elsewhere: Gage Roads No. 1 (389-619 m) 230 m. Roe No. 1 (389-616 m) ?227 m. Charlotte No. 1 (209-411 m) ?202 m.

Lithology.—The Stark Bay Formation consists dominantly of friable white bryozoan and echinodermal calcarenite, altered diagenetically in places to brown dolomite and chert, especially in the lower parts of the formation. It formed under marine conditions with virtually no terrigenous component.

Three subdivisions of the formation can be recognized, each occurring in two or more well sections. These units probably have gradational boundaries. Thicknesses given are approximate only.

Unit 1 occurs in Gage Roads No. 1 (442-619 m) and Gage Roads No. 2 (514-544 m). It is dark brown in colour and consists of chert and dolomite in equal parts, or with chert predominant.

Unit 2 occurs in Gage Roads No. 1 (389-442 m), Gage Roads No. 2 (427-514 m) and Roe No. 1 (552-616 m). It consists of brown dolomitic limestone with subordinate chert.

Unit 3 occurs in Gage Roads No. 2 (362-427 m), Roe No. 1 (?389-544 m) and Charlotte No. 1 (?209-411 m). It is in places an unaltered white friable calcarenite, probably representing the original condition of the whole formation. Elsewhere, as in Charlotte No. 1, it is somewhat recrystallised.

Fauna and age.—The formation contains in places a rich foraminiferal fauna with abundant diagnostic planktonic species. N8 and N9 are the most common ages, but the bottom of the section in Gage Roads No. 1 may be as old as N7.

Other elements of the fauna seen are echinoderm and bryozoan fragments.

Relations of boundaries.—The lower boundary is everywhere an unconformity with either Cretaceous sediments or the Palaeocene-Eocene Kings Park Formation.

The upper boundary is not well known. The formation is overlain by a red and brown recrystallised, marine limestone of indefinite age and relationship. It may be part of the same cycle of deposition but it may be separated by an unconformity.

Repository of comparative material.—Representative portions of this formation from all sections listed are in the collections of the Bureau of Mineral Resources, Canberra, and the Geological Survey of Western Australia.

Unnamed Carbonate Formation

Overlying the Stark Bay Formation in Gage Roads No. 1, Gage Roads No. 2 and probably elsewhere, is a poorly sampled, partly recrystallised red to brown limestone or dolomitic limestone unit.

It is known from ditch cuttings at 107-137 m and in a conventional core (Core 1) at about 302 m in Gage Roads No. 1. Between these intervals is a zone of lost circulation so nothing is known from this. This lithology has also been recovered from rock chips on the bit at 305 m in Gage Roads No. 2.

The formation is marine, containing foraminifera including *Operculina* and *Amphistegina*. Its exact age, and the relationships with underlying Miocene carbonates are unknown. It is discussed further below in connection with post-Miocene sedimentation.

"Rottnest Sandstone"

McWhae (*pers. comm.*) used informally the name "Rottnest Sandstone" for sediments between 71 m and 284 m in the Rottnest Island Bore. His definition is listed under discussion of that bore.

The relationships of the formation are unknown. Drillers' records (1913) of the drilled interval record "red and brown sands". This is the record that may be expected of drilling in the unnamed red and brown carbonates above the Stark Bay Formation early in this century.

It may be that the "Rottnest Sandstone" has been misinterpreted and it may prove to be an extension of the unnamed carbonate formation or its lateral equivalent. Its possible relationships are explored further below.

Post-Miocene sediments

Scattered deposits in the vicinity of Perth

Post-Miocene sediments in the Perth Basin have been little studied to date, but Kendrick (in Darragh and Kendrick, 1971, and *pers. comm.*) has examined molluscan faunas in the vicinity of Perth from shallow water bores in such places as Bullsbrook, Redcliffe, Kewdale, Gosnells, Jandakot, Peel Estate and the Gnarup district. All contain marine faunas indicating at least two periods of sedimentation, none

older than Pliocene. The materials from Lake Gnangara is only questionably Pliocene and that from Jandakot is Pleistocene.

All the Pliocene localities listed above contain the pelagic gastropod *Hartungia typica typica* Bronn which seems certainly pre-Pleistocene (Kendrick, *pers. comm.*). The species ranges back to the Miocene and Kendrick believes that the accompanying mollusc fauna is post-Miocene. Thus, a thin Pliocene marine incursion seems reasonably widespread. The lithology is usually "a grey to yellowish calcareous sandstone, often with a high proportion of quartz grains and even pebbles of crystalline rock", (Kendrick, *pers. comm.*, 21/12/1971). No formal stratigraphic terminology has yet evolved.

Following the Pliocene, probably disconformably, is Pleistocene sediment with the bivalve *Zenatiopsis ultima* Darragh and Kendrick. The extent of the Pleistocene is as yet unknown and its relationship to other young sediments (e.g., Coastal Limestone) is not yet known completely. For purposes of this work, all the Pleistocene and Pliocene is taken as a single depositional cycle, in turn consisting of several minor episodes of sedimentation.

Coastal Limestone

Overlying the Tertiary section in coastal regions and to sea is the Quaternary Coastal Limestone consisting of aeolian and marine calcareous sandstones. This reaches a maximum thickness of 70 m in the Rottnest Island Bore. Elsewhere, it is about 30 m or less.

The maximum age so far recorded is 100 000 \pm 20 000 years BP (Teichert, 1967).

Palaeoecology and palaeogeography

Post-Miocene relationships

It is clear that the two sequences of river muds are younger than or equivalent to the Coastal Limestone and that the Coastal Limestone is very Late Pleistocene to Recent (probably still forming in several places). It is thus distinctly younger than the Pliocene calcareous sandstones although the environment of formation of the marine Pliocene may be very similar to that of the marine part of the Coastal Limestone.

The relationship of the Early Pleistocene at Jandakot (Darragh and Kendrick, 1971), the "Rottnest Sandstone" and the unnamed carbonate unit overlying the Stark Bay Formation are completely unknown and there is the possibility of lateral equivalence in part.

Palaeoecology of the Stark Bay formation

While original lithology seems constant over the area covered by this formation, the contained faunas indicate quite marked environmental differences. Faunas in almost all samples from each well have constant characters but these are different from the characters in samples from neighbouring wells. Figure 5 shows the extent of the formation.

In Charlotte No. 1, planktonic percentages are very low (0-3%) throughout the section. In

Gage Roads No. 2 they are usually in the range 20-30% and in Roe No. 1, 40-70%. Figures for Gage Roads No. 1 are more difficult to obtain accurately but are low, considerably lower than in Gage Roads No. 2. Thus, some consistent bathymetric relationship holds, with the formation in Gage Roads No. 2 and Roe No. 1 representing deeper water, more open marine facies.

From planktonic percentages above, the 30 m isobath can be placed roughly between Gage Roads Nos. 1 and 2 and seaward from Charlotte No. 1.

Percentages of *Bolivina* (*sensu lato*) in a fauna also provide a depth clue. The only wells analysed with many bolivinids are Charlotte No. 1, Gage Roads No. 2 and Roe No. 1. In Gage Roads No. 2, percentages are between 1 and 3; in Charlotte No. 1, 1-6; and in Roe No. 1, normally 20-40. Again the depth gradient exists between Gage Roads No. 2 and Roe No. 1, with the latter considerably deeper.

The high bolivinid and planktonic percentages in Roe No. 1 would indicate outer continental shelf depths of the order of 100 m or more.

The fauna in Gage Roads No. 2 is of shallower aspect, but a depth more than 30 m would be expected.

The area at Charlotte and Gage Roads No. 1 was certainly inner continental shelf.

Palaeoecology in the Palaeocene-Eocene

In the Late Palaeocene and Early Eocene, sands with some marine indicators accumulated in the vicinity of Quinns Rock No. 1 (Fig. 3). At the same time, shales, limestones, etc., were deposited in a deep embayment under Perth and to the west of the mouth of this embayment at Rottnest Island and in Warnbro No. 1.

It may be coincidence, but the Swan River now, and probably then, crosses the Darling Scarp in Walyunga National Park, due east of Quinns Rock No. 1. It is now, and probably was then, a more significant stream than either the Helena or Canning Rivers which are further south.

It is here suggested that in the Late Palaeocene-Early Eocene, a significant Swan River flowed west from Walyunga and deposited sandy sediments in the vicinity of Quinns Rock No. 1. At the same time, the Canning and Helena Rivers were smaller streams flowing into a deep embayment and depositing more argillaceous sediments.

The Swan would have migrated to its present position later.

Palaeontologically significant results

Large Foraminifera in the area

A very interesting feature of the faunas in the upper part of the Stark Bay Formation in Gage Roads No. 2 (and in that well only) is the presence of a few specimens of *Lepidocyclina* (*Eulepidina*) from samples at 399 m, 427 m, 454 m and 491 m. Unfortunately, it is not known

from sidewall cores so its exact faunal associates are not known.

The specimens are characteristically very small—up to about 1.5 mm. It occurs in association with N9 planktonic foraminifera. The significance of this record of *Lepidocyclina* is manifold.

It means that warm water seas existed in the Perth area at the time. This is an extension south of about 1 000 km of the range of this genus and these conditions in W.A. The age of the occurrence seems the same as in south-eastern Australia for *L. howchini* Crespin, and the two species are very similar. This indicates strongly that warm water seas existed all around the Australian coast at this time.

L. howchini has seemed for some years to be isolated from any other Australian occurrences of the genus and its path of migration to south-eastern Australia has been conjectural. One suggestion has been that the tropical climatic zone moved south and that migration was down Australia's east coast. It is now just as likely that migration was from the west and south coasts. This fits well the present current pattern, which probably also existed in the Miocene.

The presence of the genus means that the warm water planktonic foraminiferal zonation scheme outlined by Blow (1969) can be used in the Perth Basin at this time.

The Age of the Orbulina Datum in Western Australia

Much has been written about variations in age of the influx of *Orbulina* into various sedimentary sequences on a worldwide basis. Its absolute base is N9 (Blow, 1969). Its occurrence with *Globigerinoides sicanus* in Gage Roads No. 2 (BDC at 399 m) shows that the age there is close to the base of its absolute range and the presence of *G. sicanus* with *Praeorbulina transitoria* at 579-582 m in the same well indicates that N8 is also present. *O. universa* may occur in the well as deep as 518 m, suggesting strongly that the absolute base of the range is almost surely represented in the offshore Perth Basin.

The presence of *Operculina*, *Amphistegina* and *Lepidocyclina* indicates a warm water environment, so *O. universa* could be expected to be here at the base of its range. Carter (1964) observed that in Victoria, *L. howchini* appears stratigraphically below *Orbulina universa*. In the section studied here, they are coeval and thus three possibilities arise:

1. *L. howchini* occurs earlier in the Perth Basin than in Victoria.
2. The species is the same age in both localities but the *O. universa* influx in Victoria is later than in W.A.
3. That the absence of *O. universa* in Victoria is due merely to the normal mutual exclusion of planktonic and large benthonic species.

Note added in proof.—Since presenting this paper for publication, the Mines Department of Western Australia has drilled the Claremont Asylum No. 2 bore and recovered six sidewall cores in the Kings

Park Formation. Three of these sidewall cores (68 m, 391 m and 453 m) contain planktonic foraminiferal faunas. Those from 391 m and 453 m are typical P4 Kings Park Formation faunas but that from 68 m is different. It contains *Globorotalia rex*, *G. cf. quetra*, *G. aequa*, and the important zonal species *G. pseudomenardii* and *G. chapmani* are absent.

It is probable that this fauna is P6 in age, the same as the Kings Park Formation in the Rottnest Island Bore and in Quinns Rock No. 1. It is thus the first record of rocks of this age onshore in the Perth area.

The fauna occurs in a well developed sandstone unit at the top of the Kings Park Formation. This sandstone probably can be referred to the Mullaloo Sandstone Member.

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